REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
16-02-2011	Final Report	1-Aug-2004 - 31-Jul-2008

4. TITLE AND SUBTITLE
Imaging Electron Interferometer

5a. CONTRACT NUMBER
W911NF-04-1-0343

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Robert M. Westervelt

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Harvard University
Office of Sponsored Research
1350 Massachusetts Ave. Holyoke 727
Cambridge, MA 02138 -

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
46681-PH.3

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
The research supported by this grant is aimed at imaging the flow of electron waves through a two dimensional electron gas (2DEG) to understand both the fundamental quantum behavior that appears in semiconductor nanostructures at low temperatures, and to study the propagation of electron waves through semiconductor structures with interesting geometries. A custom-made liquid He cooled scanning probe microscope (SPM) was developed in Westervelt's group to carry out the measurements. The conducting SPM tip acts as a moveable gate

15. SUBJECT TERMS
Scanning Probe Microscope, Nanostructures, Electron Transport

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Robert Westervelt
UU	UU	UU	UU		19b. TELEPHONE NUMBER: 617-495-3296

Report Title

Imaging Electron Interferometer

ABSTRACT

The research supported by this grant is aimed at imaging the flow of electron waves through a two dimensional electron gas (2DEG) to understand both the fundamental quantum behavior that appears in semiconductor nanostructures at low temperatures, and to study the propagation of electron waves through semiconductor structures with interesting geometries. A custom-made liquid He cooled scanning probe microscope (SPM) was developed in Westervelt's group to carry out the measurements. The conducting SPM tip acts as a moveable gate that locally depletes the electron gas below, creating a scattering center that reflects electron waves. By measureing the conductance of the devices as the SPM tip is raster scanned above, an image of electron flow is obtained.
Electron flow was imaged in two types of devices: (1) An Electron Interferometer, in which electron waves traveling away from a quantum point contact (QPC) reflect both from a mirror and from the depleted disc beneath the SPM tip. (2) Magnetic Focusing device, in which electrons traveling away from a QPC flow around cyclotron orbits in a perpendicular magnetic field and leave through a second QPC pointed in the same direction - a peak in conductance is observed when the spacing between the two QPCs is an integer multiple of the cyclotron diameter.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

B.J. LeRoy, A.C. Bleszynski, K.E. Aidala, R.M. Westervelt, A. Kalben, E.J. Heller, K.D. Maranowski and A.C. Gossard, "Imaging electron interferometer", Phys. Rev. Lett. 94, 126801 (2005).
D.S. Saraga, B.L. Altshuler, R.M. Westervelt and D. Loss, "Coulomb scattering in a 2D interacting electron gas and the production of EPR pairs", Phys. Rev. Lett. 92, 246803 (2004).
E.J. Heller, K.E. Aidala, B.J. LeRoy, A.C. Bleszynski, A. Kalben, R.M. Westervelt, K.D. Maranowski and A.C. Gossard, "Thermal averages with a single coherent wavepacket", Nano Letters, 5, 1285 (2005).
D.S. Saraga, B.L. Altshuler, R.M. Westervelt and D. Loss, "Coulomb scattering cross section in a 2D interacting electron gas and production of entangled electrons", Phys. Rev. B 71, 045338 (2005).
John Schliemann, Daniel Loss and R.M. Westervelt, "Zitterbewegung of electronic wavepackets in III-V zinc-blende semiconductor quantum wells", Phys. Rev. Lett. 94, 206801 (2005).
Jamie D. Walls, Jian Huang, R.M. Westervelt and Eric J. Heller, "Multiple scattering theory for two-dimensional electron gases in the presence of spin-orbit coupling", Phys. Rev. B 73, 035325 (2006).
John Schliemann, Daniel Loss and R.M. Westervelt, "Zitterbewegung of electrons and holes in III-V semiconductor quantum wells", Phys. Rev. B 73, 085323 (2006).
Katherine E. Aidala, "Imaging Magnetic Focusing in a Two-Dimensional Electron Gas," Harvard University, (2006).
Katherine E. Aidala, Robert E. Parrott, Tobias Kramer, R. M. Westervelt, Eric J. Heller, Micah P. Hanson, Arthur C. Gossard, "Imaging Magnetic Focusing of Coherent Electron Waves", Nature Physics 3, 464 (2007).
Ania C. Bleszynski-Jayich, Linus E. Fröberg, Mikael Bjork, Lars Samuelson and R.M. Westervelt "Imaging a 1-Electron InAs Quantum Dot in an InAs/InP Nanowire", Phys. Rev. B 77, 245327 (2008).

Number of Papers published in peer-reviewed journals: 10.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

R.M. Westervelt, M.A. Topinka, B.J. LeRoy, A.C. Bleszynski, K. Aidala, S.E.J. Shaw, E.J. Heller, K.D. Maranowski and A.C. Gossard, "Imaging Electron Waves", in Proc. Int. Symp. on Functional Semiconductor Nanosystems (FSNS 2003), NTT R&D Center in Atsugi, 2003, Physica E 24, 63 (2004).
A.C. Bleszynski, K.E. Aidala, B.J. Leroy, R.M. Westervelt, E.J. Heller, K.D. Maranowski and A.C. Gossard, "Imaging Electron Interferometer," Proc. 27 Int. Conf. on Physics and Semiconductors, Flagstaff, July 26-30, 2004, AIP Conf. Proc. vol. 772, 1461 (2005).
Katherine E. Aidala, Robert E. Parrott, Eric J. Heller and Robert Westervelt, "Imaging Electrons in a Magnetic Field", Proc. EP2DS, Albuquerque, July 2005, Physica E 34, 409 (2006).

Number of Papers published in non peer-reviewed journals: 3.00

(c) Presentations

Invited talk, Quantum Information Processing Workshop, Lenzerheide, Switzerland, February 16-19, 2006, "Imaging Electrons in Quantum Dots and Nanowires, and their Motion in Magnetic Fields".
Invited talk, International Nanotechnology Conference (INC2), Washington DC, May 15-17, 2006, "The Motion of Electrons inside Nanostructures".
Invited talk, Int. Conf. on Nanoscience and Technology - ICN+T 2006, Basel Switzerland, July 30-August 4, 2006, "Imaging Electrons in Quantum Dots and Nanowires, and their Motion in Magnetic Fields".
Physics Colloquium, Carnegie Mellon University, October 30, 2006, "Imaging Electrons in Nanodevices".
Physics Colloquium, Univ. of Illinois at Urbana Champaign, January 25, 2007, "Imaging Electrons in Nanodevices".
Plenary Talk, Int. Conf. on Nanoelectronics, Nanostructures and Carrier Interactions (NNCI 2007), February 20-23, 2007, NTT Basic Research Lab, Atsugi, Japan, "Imaging Electrons in Nanodevices".
Seminar, March 13, 2007, NTT Basic Research Lab, Atsugi, Japan, "Imaging Electrons in Nanodevices."
Seminar, April 16, 2007, University of Tokyo, "Imaging Electrons in Nanodevices." Seminar, April 17, 2007, Tokyo Institute of Technology, "Imaging Electrons in Nanodevices."
Plenary Talk, Int. Conf. on Nanoscience and Technology (ICN+T 2007), Stockholm, Sweden, July 2-6, 2007, "Imaging Electrons in Nanoscale Devices".
Colloquium, Luft University, Sweden, July 11, 2007, "Imaging Electrons in Nanoscale Devices."
Invited Talk, Univ. of Tokyo, Komaba Campus, "Imaging Electrons in Nanodevices," December 24, 2008, Tokyo, Japan.
Invited Talk, Center for Probing the Nanoscale Workshop, Stanford University, “Imaging Quantum Devices, May 24, 2009, Stanford University.

Number of Presentations: 13.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
Katherine e. Aidala	1.00
Ania Bleszynski	
FTE Equivalent:	**1.00**
Total Number:	**2**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Robert M Westervelt	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Katherine E. Aidala
Ania Bleszynski
Total Number: **2**

Names of other research staff

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Electron Interferometer - An interferometer for electron waves was constructed in a two dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure (LeRoy et al. 2005, Heller et al. 2005). Electron waves passing from a quantum point contact (QPC) were simultaneously reflected by a mirror produced by a curved gate, and by the depleted disc underneath a charged SPM tip. At the tip is scanning above the sample, interference fringes are observed in it's conductance, separated by half the Fermi wavelength, analogous to what one sees in an optical interferometers.

Design and Fabrication of a Liquid He Cooled Scanning Probe Microscope - Kathy Aidala designed, fabricated and tested a liquid He cooled scanning probe microscope (SPM) for use in imaging electron waves for the supported research (Aidala 2006). This is a new design that includes a superconducting solenoid to generate a strong magnetic field.

Imaging the Cyclotron Orbit of Electrons in a 2DEG by Magnetic Focusing - Aidala used the cooled SPM to image the cyclotron orbit of electrons traveling through a 2DEG (Aidala 2006, Aidala et al. 2007). Magnetic focusing is an effect originally discovered in metals in the 1960's. For a 2DEG, magnetic focusing occurs when electrons passing out of one QPC travel in a circular path along a cyclotron orbit and pass into a second QPC located at a distance which is an integer number of cyclotron diameters away. Aidala imaged the cyclotron orbit by deflecting electrons with the SPM tip. In addition to the orbit, she observed fringes caused by the interference of electron waves traveling along two paths simultaneously.

Theoretical Simulations of Electron Flow - Westervelt collaborated with several theorists to develop ways to image quantum phenomena using a cooled SPM: Production of entangled electron pairs via controlled collisions (Saraga et al. 2004, 2005); Imaging of zitterbewegung of electron wavepackets in III-V quantum wells using a cooled SPM (Schliemann et al. 2005, 2006), and the effects of spin-orbit scattering (Walls et al. 2006).

Technology Transfer

FINAL REPORT (2004-2007)
ARO W911NF-04-1-0343
"Imaging Electron Interferometer"
PI R.M. Westervelt
Total support 11/04-7/07: $300,000

(1) Forward (optional): see below

(2) Table of Contents: N/A

(3) List of Appendices: N/A

(4) Statement of Problem Studied

The research supported by this grant is aimed at imaging the flow of electron waves through a two dimensional electron gas (2DEG) to understand both the fundamental quantum behavior that appears in semiconductor nanostructures at low temperatures, and to study the propagation of electron waves through semiconductor structures with interesting geometries. A custom-made liquid He cooled scanning probe microscope (SPM) was developed in Westervelt's group to carry out the measurements. The conducting SPM tip acts as a moveable gate that locally depletes the electron gas below, creating a scattering center that reflects electron waves. By measureing the conductance of the devices as the SPM tip is raster scanned above, an image of electron flow is obtained.

Electron flow was imaged in two types of devices: (1) An Electron Interferometer, in which electron waves traveling away from a quantum point contact (QPC) reflect both from a mirror and from the depleted disc beneath the SPM tip. (2) Magnetic Focusing device, in which electrons traveling away from a QPC flow around cyclotron orbits in a perpendicular magnetic field and leave through a second QPC pointed in the same direction - a peak in conductance is observed when the spacing between the two QPCs is an integer multiple of the cyclotron diameter.

(5) Summary of Most Important Results (2004-2007):

Electron Interferometer - An interferometer for electron waves was constructed in a two dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure (LeRoy *et al.* 2005, Heller *et al.* 2005). Electron waves passing from a quantum point contact (QPC) were simultaneously reflected by a mirror produced by a curved gate, and by the depleted disc underneath a charged SPM tip. At the tip is scanning above the sample, interference fringes are observed in it's conductance, separated by half the Fermi wavelength, analogous to what one sees in an optical interferometers.

Design and Fabrication of a Liquid He Cooled Scanning Probe Microscope - Kathy Aidala designed, fabricated and tested a liquid He cooled scanning probe microscope (SPM) for use in imaging electron waves for the supported research (Aidala 2006). This is a new design that includes a superconducting solenoid to generate a strong magnetic field.

Imaging the Cyclotron Orbit of Electrons in a 2DEG by Magnetic Focusing - Aidala used the cooled SPM to image the cyclotron orbit of electrons traveling through a 2DEG (Aidala 2006, Aidala *et al.* 2007). Magnetic focusing is an effect originally discovered in metals in the 1960's. For a 2DEG, magnetic focusing occurs when electrons passing out of one QPC travel in a circular path along a cyclotron orbit and pass into a second QPC located at a distance which is an

integer number of cyclotron diameters away. Aidala imaged the cyclotron orbit by deflecting electrons with the SPM tip. In addition to the orbit, she observed fringes caused by the interference of electron waves traveling along two paths simultaneously.

Theoretical Simulations of Electron Flow - Westervelt collaborated with several theorists to develop ways to image quantum phenomena using a cooled SPM: Production of entangled electron pairs *via* controlled collisions (Saraga *et al.* 2004, 2005); Imaging of zitterbewegung of electron wavepackets in III-V quantum wells using a cooled SPM (Schliemann *et al.* 2005, 2006), and the effects of spin-orbit scattering (Walls *et al.* 2006).

(6) Publications Supported by the Grant (2004-2007):

(a) Papers published in peer-reviewed journals

B.J. LeRoy, A.C. Bleszynski, K.E. Aidala, R.M. Westervelt, A. Kalben, E.J. Heller, K.D. Maranowski and A.C. Gossard, "Imaging electron interferometer", Phys. Rev. Lett. **94**, 126801 (2005).

D.S. Saraga, B.L. Altshuler, R.M. Westervelt and D. Loss, "Coulomb scattering in a 2D interacting electron gas and the production of EPR pairs", Phys. Rev. Lett. **92**, 246803 (2004).

E.J. Heller, K.E. Aidala, B.J. LeRoy, A.C. Bleszynski, A. Kalben, R.M. Westervelt, K.D. Maranowski and A.C. Gossard, "Thermal averages with a single coherent wavepacket", Nano Letters, **5**, 1285 (2005).

D.S. Saraga, B.L. Altshuler, R.M. Westervelt and D. Loss, "Coulomb scattering cross section in a 2D interacting electron gas and production of entangled electrons", Phys. Rev. B **71**, 045338 (2005).

John Schliemann, Daniel Loss and R.M. Westervelt, "Zitterbewegung of electronic wavepackets in III-V zinc-blende semiconductor quantum wells", Phys. Rev. Lett. **94**, 206801 (2005).

Jamie D. Walls, Jian Huang, R.M. Westervelt and Eric J. Heller, "Multiple scattering theory for two-dimensional electron gases in the presence of spin-orbit coupling", Phys. Rev. B **73**, 035325 (2006).

John Schliemann, Daniel Loss and R.M. Westervelt, "Zitterbewegung of electrons and holes in III-V semiconductor quantum wells", Phys. Rev. B **73**, 085323 (2006).

Katherine E. Aidala, "Imaging Magnetic Focusing in a Two-Dimensional Electron Gas," Harvard University, (2006).

Katherine E. Aidala, Robert E. Parrott, Tobias Kramer, R. M. Westervelt, Eric J. Heller, Micah P. Hanson, Arthur C. Gossard, "Imaging Magnetic Focusing of Coherent Electron Waves", Nature Physics **3**, 464 (2007).

Ania C. Bleszynski-Jayich, Linus E. Fröberg, Mikael Bjork, Lars Samuelson and R.M. Westervelt "Imaging a 1-Electron InAs Quantum Dot in an InAs/InP Nanowire", Phys. Rev. B **77**, 245327 (2008).

(b) Papers published in non-peer reviewed journals or in conferences

R.M. Westervelt, M.A. Topinka, B.J. LeRoy, A.C. Bleszynski, K. Aidala, S.E.J. Shaw, E.J. Heller, K.D. Maranowski and A.C. Gossard, "Imaging Electron Waves", in *Proc. Int. Symp. on Functional Semiconductor Nanosystems* (FSNS 2003), NTT R&D Center in Atsugi, 2003, Physica E **24**, 63 (2004).

A.C. Bleszynski, K.E. Aidala, B.J. Leroy, R.M. Westervelt, E.J. Heller, K.D. Maranowski and A.C. Gossard, "Imaging Electron Interferometer," *Proc. 27 Int. Conf. on Physics and Semiconductors, Flagstaff, July 26-30, 2004*, AIP Conf. Proc. vol. **772**, 1461 (2005).

Katherine E. Aidala, Robert E. Parrott, Eric J. Heller and Robert Westervelt, "Imaging Electrons in a Magnetic Field", *Proc. EP2DS, Albuquerque, July 2005*, Physica E **34**, 409 (2006).

(c) Papers presented at meetings, but not published in conference proceedings: N/A

(d) Manuscripts submitted, but not published: N/A

(e) Technical reports submitted to ARO: N/A

Invited Talks (R.M. Westervelt) Supported by Grant (2004-2007)

Invited talk, Quantum Information Processing Workshop, Lenzerheide, Switzerland, February 16-19, 2006, "Imaging Electrons in Quantum Dots and Nanowires, and their Motion in Magnetic Fields".

Invited talk, International Nanotechnology Conference (INC2), Washington DC, May 15-17, 2006, "The Motion of Electrons inside Nanostructures".

Invited talk, Int. Conf. on Nanoscience and Technology - ICN+T 2006, Basel Switzerland, July 30-August 4, 2006, "Imaging Electrons in Quantum Dots and Nanowires, and their Motion in Magnetic Fields".

Physics Colloquium, Carnegie Mellon University, October 30, 2006, "Imaging Electrons in Nanodevices".

Physics Colloquium, Univ. of Illinois at Urbana Champaign, January 25, 2007, "Imaging Electrons in Nanodevices".

Plenary Talk, Int. Conf. on Nanoelectronics, Nanostructures and Carrier Interactions (NNCI 2007), February 20-23, 2007, NTT Basic Research Lab, Atsugi, Japan, "Imaging Electrons in Nanodevices".

Seminar, March 13, 2007, NTT Basic Research Lab, Atsugi, Japan, "Imaging Electrons in Nanodevices."

Seminar, April 16, 2007, University of Tokyo, "Imaging Electrons in Nanodevices."

Seminar, April 17, 2007, Tokyo Institute of Technology, "Imaging Electrons in Nanodevices."

Plenary Talk, Int. Conf. on Nanoscience and Technology (ICN+T 2007), Stockholm, Sweden, July 2-6, 2007, "Imaging Electrons in Nanoscale Devices".

Colloquium, Luft University, Sweden, July 11, 2007, "Imaging Electrons in Nanoscale Devices."

Invited Talk, Univ. of Tokyo, Komaba Campus, "Imaging Electrons in Nanodevices," December 24, 2008, Tokyo, Japan.

Invited Talk, Center for Probing the Nanoscale Workshop, Stanford University, “Imaging Quantum Devices, May 24, 2009, Stanford University.

(7) Participating Scientific Personnel

Robert M. Westervelt - PI of the grant

Katherine E. Aidala (PhD obtained during project) - Kathy designed and constructed a liquid He cooled Scanning Probe Microscope for imaging electron flow inside semiconductors. She used this instrument to image the cyclotron orbit of electrons in a two-dimensional electron gas through magnetic focusing in the flow between two quantum point contacts. Kathy Aidala is currently an Asst Professor at Mt Holyoke College.

Ania Bleszynski (PhD obtained during project) - This grant supplied partial support for Ania's research to control few electron quantum dots grown inside InAs/InP nanowire heterostructures. Ania is currently an Asst Professor at the University of California, Santa Barbara.

(8) **Report of Inventions**: N/A

(9) **Bibliography** (see publications above)

(10) **Appendices**: N/A